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ABSTRACT

Background: The Hintegra® arthroplasty provides inversion-eversion stability, permits axial rotation, ankle flexion-extension, and improvements of the gait patterns are expected up to 12 months of rehabilitation. However, sensorimotor impairments are observed in ankle flexors/extensors muscles after rehabilitation, with potential negative effects on locomotion. Here we determined the timing and amplitude of co-activation of the tibialis anterior and medial gastrocnemius muscles during gait by assessing non-operated and operated legs of patients with total ankle replacement, 5 years after surgery.

Methods: Twenty-nine patients (age: 58 [5.5] years, height: 156.4 [6.5] cm, body mass: 72.9 [6.5] kg, 10 men, and 19 women) that underwent Hintegra® ankle arthroplasty were included. Inclusion criteria included 5 years prosthesis survivorship. The onset and offset of muscle activation (timing), as well as the amplitude of activation, were determined during barefoot walking at self-selected speed by surface electromyography. The timing, percentage, and index of co-activation between the tibialis anterior and medial gastrocnemius were quantified and compared between non-operated and operated legs.

Findings: The operated leg showed higher co-activation index and temporal overlapping between tibialis anterior and medial gastrocnemius during gait ($P < .001$).

Interpretation: The neuromuscular changes developed during the process of degeneration do not appear to be restored 5 years following arthroplasty. The insertion of an ankle implant may restore anatomy and alignment but neuromuscular adaptations to degeneration are not corrected by 5 years following joint replacement.

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1. Introduction

Lower limb osteoarthritis is associated with pain and impaired function with negative effects on locomotion. More specifically, ankle osteoarthritis impairs sagittal plane motion (dorsiflexion and plantarflexion) and torque (Al-Mohrougi et al., 2018). In many cases the joint degeneration will reach levels that require the total joint replacement. Ankle arthroplasty is a surgical procedure in which the tibiotalar joint is replaced (Giannini et al., 2000; Caravaggi et al., 2015). Eighty percent of candidates are patients who developed ankle osteoarthritis secondary to trauma (post-traumatic etiology) (Horisberger et al., 2009; Bloch et al., 2015), with far fewer outcomes reported compared to hip and knee arthroplasty (Al-Mohrougi et al., 2018). In the past 40 years more than 30 models of ankle prosthesis have been introduced, with few outcomes against hip and knee arthroplasty (Giannini et al., 2000; Henricson et al., 2011). In this regard, Hintegra® arthroplasty is a third generation prosthesis that provides inversion-eversion stability, permits axial rotation, ankle flexion-extension being one of the few ankle prosthesis showing good results concerning activities of daily living (Michael et al., 2008; Hintermann, 2005). Previous studies showed that the Hintegra prosthesis is built with stable components, with low rate of complications (Michael et al., 2008; Hintermann, 2005; Barg et al., 2011), allowing an adequate range of motion (Valderrabano et al., 2003; Michael et al., 2008; Hintermann, 2005). However, the lack of restoration of gait symmetry and joint function remains a problem after ankle arthroplasty (Caravaggi et al., 2015).

During the first year after Hintegra® arthroplasty, there are adaptations in the first three months of rehabilitation that negatively affects the gait biomechanics. These include lower maximal plantar-flexion moment, total adduction moment, medial ground reaction force, and higher anterior ground reaction force during gait by increasing mechanical loading on knee joint (Valderrabano et al., 2007). This adaptive period was previously reported as negative phase of rehabilitation (De la Fuente et al., 2014). These parameters are expected to improve towards the end of the first year after surgery (Valderrabano et al., 2007), with significant improvement of gait pattern (Valderrabano et al., 2007; Aidi et al., 2013) and quality of life (Esparragoza et al., 2011). It has been suggested that 5 years following total ankle joint replacement there is an increase in the American Orthopaedic Foot and Ankle Score (Zaidi et al., 2013). However, there is little information concerning the effect of ankle replacement on neuromuscular activity of ankle muscles (tibialis anterior and medial gastrocnemius) (Doets et al., 2007). Abnormal muscle co-activation could result in increased and abnormal kinetics on the prosthesis predisposing to loosening. Presumably the prosthesis is designed to replicate normal anatomy of the ankle joint. If however the muscular co-activation does not change the forces will remain high.

An adequate control of tibialis anterior and medial gastrocnemius muscles depends both on the timing of agonist and antagonist activation (Hubley-Kozey et al., 2010; Rosa et al., 2010), and the intensity of their contractions, i.e. weight coefficients (Cappelini et al., 2006). These muscles sometimes present co-activation, an involuntary and concurrent activation of the antagonist, in opposition to the contraction of the agonist (Duchateau et al., 2014). Changes in co-activation occur during different physical activities e.g. running compared to walking (Cappelini et al., 2006), footwear selection (Alkjær et al., 2012) and in pathological processes e.g. cerebellar ataxia (Mari et al., 2014), foot and knee motor functions (Di Nardo et al., 2015), and ankle osteoarthritis (Von Tscharner & Valderrabano, 2010). Furthermore, co-activation may affect gait pattern and the integrity of prostheses due to abnormal joint force development (De la Fuente et al., 2014).

After the Hintegra® arthroplasty placement, the gait pattern is expected to be restored, and co-activation between tibialis anterior and medial gastrocnemius should not occur at medium term after the first three months of rehabilitation (Michael et al., 2008; Hintermann, 2005). However, there is a lack of evidence concerning patterns of co-activation after ankle replacement when rehabilitation is completed. Therefore, here we determine the relative measures of amplitude and timing of co-activation of the tibialis anterior and medial gastrocnemius muscles during gait, by comparing the electromyographic activity of the non-operated and operated leg of patients with total ankle replacement, 5 years after surgery. Our null-hypotheses were: i) total ankle replacement after 5 years does not recover the timing of co-activation to the level of the non-operated leg during gait; ii) total ankle replacement after 5 years does not recover the temporal percentage of co-activation to the level of the non-operated leg during gait, and ii) total ankle replacement after 5 years does not recover the index of co-activation to the level of the non-operated leg during gait.

2. Methods

2.1. Study design

This is a cross-sectional, observational, analytical study design. The sample included twenty-nine patients (10 men and 19 women) that underwent unilateral total ankle replacement 5 years before the measurement session in which the operated and non-operated leg were compared during gait. The inclusion criteria were: i) unilateral total ankle replacement with Hintegra® arthroplasty (Newdeal SA, Vienne, France); ii) at least 5 years following replacement; iii) rehabilitation treatment of one year; iv) posttraumatic arthritis; v) age between 40 and 70 years old; vi) passive dorsal range of motion greater than 5º at the sagittal plane (De la Fuente et al., 2014); vi) radiological stability (Horisberger et al., 2009; Bai et al., 2010; Guyer and Richardson, 2008); and v) have been rehabilitated at the *Instituto Traumatológico* (Santiago, Chile) by the same surgical and rehabilitation team. The exclusion criteria were: i) need for assisted locomotion; ii) major limitations in performance of daily life activities; iii) major periarticular tissue impairment; iv) ipsilateral or contralateral hip/knee osteoarthritis; v) inflammatory diseases; vi) neurological pathology; vii) active infection; and viii) cognitive impairment (von Tscharner and Valderrabano, 2010). This study was approved by the institutional review board of the *Instituto Traumatológico* (Santiago, Chile) according to the principles of the Declaration of Helsinki. All participants signed a consent term agreeing to participate in this study.

2.2. Sample size

The sample size was estimated "a priori" with a pilot experiment that included 6 patients [mean (standard deviation) 56.5 (2.1) years-old, 30.1 (1.8) kg/m^2, 3 men and 3 women] that fulfilled the inclusion and exclusion criteria. A sample size of 23 patients was estimated considering a difference between two dependent means (matched pairs), using two-tailed *t*-test with alpha error of 5% and statistical power of 80% for an estimated effect size of 0.62. Six additional patients were included to the sample to anticipate possible attrition (20% of estimation). The total patients assessed were 35 patients; 6 patients from the "a priori" determination of sample size and additional 29 patients. The statistical calculus was performed by G*Power software version 3.1.9.2. (Kiel University, Germany).

2.3. Surgery and physical therapy procedures

All participants had a Hintegra® prosthesis (Hintermann, 2005) (Newdeal SA, Vienne, France). In general terms, surgery involved an anterior longitudinal incision of 10 to 12 cm performed to dissect the retinaculum. Moreover, the soft tissue and periosteum from the bone were dissected. Resection of the talus and tibia were performed to insert arthroplasty components using Hintermann® distractor and oscillating saw. Osteophytes on the talar neck and anterior aspect of medial malleolus were also removed. After that, the tibial and talar components were inserted. The last inserted component was the polyethylene component. The tissues were sutured, and the procedure was finalized by fitting a short leg cast. The patients were monitored for the next three weeks after surgery, once per week, and during the first 4 weeks after surgery patients were immobilized with a short leg cast and instructed to unload the operated leg and rest.

The physiotherapy intervention was performed from week 4 until week 52 (Ingrosso et al., 2009). From the week 4 to 12, the patients attended the rehabilitation service, where they used a walking boot. In this period, partial weight bearing was permitted using the assistance of canes. Furthermore, stretching to improve the dorsal flexion range of motion, strengthening of ankle, knee and hip muscles, and pain relief with physical agents were activities performed. The re-education of gait without assistance, bipedal heel rise, balance exercises, and pain relief management were performed until the end of week 52 (Martin et al., 2007). Afterwards, patients returned to the to the foot and ankle hospital unit every six months to be assessed in the follow-up period.

2.4. Data acquisition and processing

The data acquisition consisted of two stages: clinical assessment and surface electromyography recordings. The patients attended an interview, and the clinical assessment was performed at the foot and ankle service of the *Instituto Traumatológico* (Santiago, Chile). The age, body mass, height, AOFAS score (Kitaoka et al., 1994), passive dorsiflexion range of movement, difference in calf whilst standing (Saxena et al., 2011; Valdebarrano et al., 2006), and intensity of pain at rest and during walking assessed with a numerical verbal scale (0 no pain, 10 maximum possible pain) (Hintermann, 2005) and were part of the clinical assessment.

Surface electromyography recordings were performed one week after the clinical assessment at the *Centro de Investigaciones Medicas del Instituto Traumatológico* (Santiago, Chile). After a 5-min warm-up on a cycloergometer without external load and cadence of 60 rpm, patients walked barefoot at self-selected speed (von Tscharner and Valdebarrano, 2010; De la Fuente et al., 2014) along a 5-meter flat surface on a straight-line. Patients performed five trials for familiarization within the walking space. Although we did not measure kinematics, a common heel strike pattern was observed among the patients. The electromyography signals were acquired during walking using a Myomonitor IV electromyography amplifier (Delsys, inc., Boston, USA). Two DE-2.3 single differential surface electromyography sensors (Delsys, inc., Boston, USA) with an inter-electrode distance of 10 mm were used. The data collection employed a 16-bit analog-digital converter card (National Instrument Corp., Austin, TX, USA) operated by a Matlab software (Mathworks Inc., Massachusetts, USA) at a sampling rate of 1000 Hz, band-pass filtered (20–450 Hz), and hardware amplified with a gain of 1000 V/V. The muscles assessed were tibialis anterior and medial gastrocnemius based on their lower mean electromyography frequency and intensity previously found by Valderrabano et al. (2006) in unilateral ankle osteoarthritis, and the hypothesis of Doets et al. (2007), who suggested that after ankle joint replacement, higher co-activation between these muscles could exist during gait. The surface electromyography sensors were placed according to the European recommendations for surface electromyography (Hermens et al., 2000).

2.5. Signal treatment

The electromyography signals were filtered by a zero-lag 4th order finite impulse response Butterworth with a band pass of 20 to 450 Hz. Onset and offset times of muscle activation (Caravaggi et al., 2015) were identified using a continuous wavelet with the algorithm proposed by Merlo et al. (2003). The algorithm was performed using the Hermite-Rodriguez mother wavelet, 10% of noise power, 150 ms for the time of two detected activation intervals, and 5 ms for the spike rejection from non-rectified signals. The noise of electromyography signals was extracted when patients stood quietly before walking. Five consecutive electromyography bursts of the tibialis anterior and gastrocnemius medialis (corresponding to 5 strides) were used for the analysis.

All signals were full wave rectified (Figure 1). Due to the variability and non-accordance of normalization methods for analysis of electromyography signals (Rosa et al., 2010), a standardized treatment of signals by z-score method was performed. Each sample was subtracted from its expected value (E[X]) and divided by the standard deviation. This expresses the number of standard deviations by which the sample is above the E[X]. As the whole electromyography signals showed a normal distribution, the z-score was obtained using the arithmetic mean of the data.

2.6. Outcomes

The timing of co-activation: determined by the time overlap between the onsets and offsets activation (Rosa et al., 2010).

Percentage of co-activation: from the time activation onsets and offsets, the percentage of co-activation was quantified as the overlapped percentage of muscle activation (Rosa et al., 2010).

Co-activation index: determined by the overlapped amplitudes of muscle activation between the tibialis anterior and medial gastrocnemius. The co-activation index was implemented in discrete form by the trapezoidal method (Eq. 1) from the original continuous form previously defined in the literature (Rosa et al., 2010).

$$Coactivion\ index = 2 \times \frac{\sum_{CoAc_{onset}}^{CoAc_{offset}}\left[\frac{(X_{i+1} - X_i)}{2} \times \Delta t\right]}{\sum_{Agonist}^{Antagonist}\left[\sum_{onset}^{offset}\frac{(X_{i+1} - X_i)}{2} \times \Delta t\right]_j} \times 100\% \qquad \text{(Eq. 1)}$$

In the equation 1, $CoAc_{onset/offset}$ is the co-activation time of onset or offset, x_i is the electromyography sample, Δt is the interval time of data acquisition given the sampling frequency, and j represents the agonist or antagonist condition. To assess the intensity of concurrent contractions, the trapezoidal areas were obtained using the “cumtrapz function” from the full-rectified signals using the Matlab software (Mathworks Inc., Massachusetts, USA).

2.7. Statistical analysis

Data were reported as the median and interquartile range [IQ range] because the Shapiro-Wilk test revealed a non-parametric data distribution. Homoscedasticity was confirmed using the Levene’s test. To compare the timing, percentage, and index of co-activation of medial gastrocnemius and tibialis anterior between the operated and non-operated legs, a Wilcoxon Signed-Ranks test of two-tails was used with alpha error equal to 5%. To assess the possible existence of co-variable and interaction with outcomes, a multiple regression respect to analysis for age, body mass, height, AOFAS score, the passive dorsal range of movement, calf circumference difference between leg during a standing posture, the intensity of pain at rest and during gait were considered at $p<0.05$. Data were analyzed using the Matlab software statistical toolbox (Mathworks Inc., Massachusetts, USA).

3. Results

The timing of co-activation between the tibialis anterior and medial gastrocnemius in the non-operated leg [median: 390 ms, IQ range: 80 ms] was lower than in the operated leg [median: 566 ms, IQ range: 104 ms, $p<0.001$]. The percentage of co-activation between the tibialis anterioris and gastrocnemius medialis in the non-operated leg [median: 0.00 %, IQ range: 1.84 %] was lower than in the operated leg [median: 100%, IQ range: 0.00 %$p<0.001$]. The index of co-activation between the tibialis anterior and medial gastrocnemius in the non-operated leg [median: 0.00 %IQ range: 1.94 %] was lower than in the operated leg [median: 30.96%, IQ range: 13.52%, $p<0.001$]. The changes in co-activation are depicted in the Figure 1.

The demographic characteristics of the sample regarding age, body mass, height, AOFAS score, passive dorsal range of movement, calf circumference difference between legs during standing posture, intensity of pain at rest, and during gait did not co-vary or interacted with any of the electromyography outcomes ($p>0.05$).

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4. Discussion

The most important finding of this work was that patients with the Hintegra® arthroplasty present abnormal plantar and dorsi-flexion co-activation patterns during gait after 5 years following total ankle joint replacement. Although the patients did not receive rehabilitation after 5 years following total ankle joint replacement due to the improvement observed in the AOFAS score, the present findings suggest the need for an appropriate sensorimotor rehabilitation program for patients in which problems at medium term of survival of the prosthesis still persist.

Although it can’t be ensured (due to the lack of kinetics and kinematics assessment), the altered co-activation found in our study may suggest that both absorption and propulsion phases of walking could be committed 5 years after replacement surgery. Dorsal and plantar-flexor muscles need to be activated during different phases of gait in order to maintain the normal mechanics of the ankle joint during swing and load response. This is important for the control of the anterior advance of the tibia or the generation of propulsion. Therefore, these mechanical actions need temporal muscle coordination (timing of activation). Based on the findings from Di Nardo et al. (2015) and Cappellini et al. (2006), the tibialis anterior and medial gastrocnemius muscles should present independent temporal activations during the different phases of normal gait (low speed). It contrasts with the results of patients treated with ankle prosthesis, since a temporal overlap between these muscles was found.

Based on the findings from Siegler et al. (2013), an altered kinetic condition can be present in patients with Hintegra® arthroplasty. Siegler et al. (2013) tri-dimensionally modeled the talus of 26 healthy adults and found that "the trochlear surface can be modeled as a skewed truncated conic saddle shape with its apex oriented laterally rather than medially", which contrasts with the mechanical model of Inman, in which the Hintegra® arthroplasty is based (Hinterman 2005). Thus, the mechanical design of the Hintegra® arthroplasty could alter distribution or intensity of ankle joint forces during the stance phase, or both, such as the abnormal joint shear forces and delayed the first peak of vertical ground reaction force found after the negative rehabilitation phase in patients treated with an Hintegra® arthroplasty (De la Fuente et al., 2014). Our data suggests that these mechanical changes could result of sensorimotor adaptations, since an increased co-activation between dorsal and plantar flexors would reduce the velocity of the foot and tibia during stance phase, which reduces the vertical component of the ground reaction force at load response phase. However, an increased co-activation might also result of intrinsic instability of the prosthesis in the frontal plane, which could have an unstable effect over the foot based on mechanical findings from Siegler et al. (2013), further leading to the shifting of the medial gastrocnemius rather than a shift of the tibialis anterior activation, as shown here.

As the shifting in the medial gastrocnemius could occur, the propulsion phase might also be affected (Giannini et al., 2000; Henricson et al., 2011). This possible change is in accordance with de la Fuente et al. (2014), who proposed a gait pattern with external hip rotation that increases the activity of hip extensors (rather than plantar flexors) to generate the propulsion of the leg with Hintegra® arthroplasty, after the negative rehabilitation phase. Therefore, it is possible that patients with Hintegra® arthroplasty experience an over-stabilization of the ankle joint after at medium term, affecting the whole pattern of gait by an unstable load response and altered propulsion phase. This hypothesis still needs to be investigated.

On the other hand, Stubbs et al. (1998) suggested that the load over viscoelastic tissues creates a sensorimotor response called "muscle-ligament reflex" causing an altered activity of agonist and antagonist muscles over time. Therefore, the surgery itself could cause the neuromuscular changes observed, since the tibialis anterior and ankle ligaments must be pulled to introduce the arthroplasty components into the ankle joint space. This is important as one wonders if neuromuscular changes are reversible with time. Our findings would suggest that at 5 years after ankle replacement they are not reversible. In making this statement perhaps prosthesis designers would be better to use an arthroplasty designed to tolerate the irreversible forces on the prosthesis. Finally, chronic pain could be another source of the neuromuscular changes observed in our study. Valderrabano et al., (2006) and von Tscharner et al. (2010) described that the time of exposure to pain in osteoarthrosis is the worst stimulus to the nervous system changing the neuromuscular patterns of activations. This could induce changes in the ankle stiffness leading to pathological neuroplasticity changes, possibly present since before the arthroplasty surgery. However, in our study, the intensity of pain was not identified as a co-variable and did not show any interaction with the outcomes.

Due to the higher co-activation found in patients with Hintegra® arthroplasty at 5 years after ankle replacement, new rehabilitation approaches are needed to improve the locomotion in patient who shows the sensorimotor impairments described here. To our knowledge, this is the first pathological report at medium term in patients with Hintegra® arthroplasty. Future studies should identify *in vivo* whether the ankle axis of this arthroplasty is really positioned as Inman previously reported, since alterations in the prosthesis axis of rotation could lead to the sensorimotor impairments found. Also, the presence of other concomitant musculoskeletal problems (e.g., knee, hip or trunk disorders, metatarsal-cunieform, cuneiform-navicular and talo-navicular osteoarthritis) requires further examination. Finally, it is important to investigate whether previous pathological sensorimotor conditions acquired before the arthroplasty are irreversible after the surgery (i.e., chronic pain). Regarding the limitations of our study, the sample is only representative of patients with lower AOFAS score, in contrast to the results with Hintegra® (Hinterman, 2005) and other arthroplasties (Aidi et al., 2013; Caravaggi et al., 2015). Also, the measurement of pain considered a verbal pain scale (Hinterman, 2005), which may not reflect the sensorimotor impartments showed by previous studies (Ervilha et al., 2004; Lindstrøm et al., 2011). Finally, we propose that a detailed mechanical analysis of gait, in addition to the analysis of co-activation alteration, is needed to understand the possible neuro-mechanical pathological new hypotheses discussed in our study.

5. Conclusions

Altered co-activation during gait is present after at 5 years after total ankle replacement with the Hintegra® prosthesis. It may result of an attempt to compensate ankle instabilities following arthroplasty, which effects on gait dynamics require attention during rehabilitation programs.

Conflict of interests

The authors declare no conflicts of interest.

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Figure caption

Figure 1. Temporal co-activation between medial gastrocnemius and tibialis anterior during gait in the non-operated (top) and operated (bottom) legs from patient 1. The EMG signals of the medial gastrocnemius are shown in light gray and positive values. The tibialis anterior signals are shown in dark gray and negative values. The line shows the identified time of muscle activity as proposed by Merlo et al (2003). The upper box shows the color intensity scale of the temporal overlapping relative to the medial gastrocnemius. The bottom boxes show the intensity of each overlap found. The signals were normalized in function of z-score.